Linking Urban Residential Landscape Types in a Desert Environment to Landscape Water Budgets

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SUMMARY. Linking an urban residential landscapes type to a specific landscape water budget is important to water resource management in a desert environment. Yet, no research that we are aware of has effectively associated a specific water budget with a quantitatively determined urban landscape type. The objective of this research was to determine whether a landscape water budget and residential urban landscape type could be related. We previously quantitatively classified urban residential landscapes in the desert environment of Las Cruces, NM, into hard-surface shade-structure, mulch, hard-surface, hard-surface-mulch, mulch tree, turf mulch, turf, tree mulch turf, and turf tree landscape types. In this study, we determined water budget, landscape coefficient, and the portion of the coverage of irrigated and nonirrigated elements for each landscape type. Landscape types in Las Cruces grouped into four distinct water budget groups: no-water, low-, moderate-, and high-water budget. Because of the heterogeneity of the coefficients for grass, plants, and water surfaces that constituted it, the landscape coefficient correlated weakly ($r^2 = 0.3$) with the water budget. Coverage of the irrigated elements correlated highly ($r^2 = 0.95$) with the water budget. Our results suggest that the coverage of irrigated elements in a desert urban landscape is a major driver of landscape water budgets.

In desert communities, residents aspire to balance their preferred landscape with the need for water conservation (Spinti et al., 2004). This balance is a challenge for homeowners who desire to select their favorite landscape, but do not know the water needs of their choice. Knowledge of the water needs of landscape types can be a major strategy in urban water conservation (Hurd et al., 2006).

Traditionally, a landscape water budget has been defined as the amount of water required to maintain water features in a landscape and irrigate plants to nonstress conditions (Al-Kofahi et al., 2012a; St. Hilaire et al., 2008). However, St. Hilaire et al. (2008) cautioned that many landscape groundcovers and shrubs

have acceptable aesthetic performance without irrigation or with reduced irrigation. Recognizing the potential impact of landscape selection on water budgets of desert urban landscapes, Hurd et al. (2006) presented a drawing of a landscape to residents of Albuquerque, Las Cruces, and Santa Fe, NM, that showed various configurations of a 2500-ft² landscapable area around an urban residence. Estimated yearly water use values for the configurations varied from 40,000 gal when that landscape had 100% turf to 15,000 gal when that landscape had no turf and 100% drought-tolerant trees, shrubs, native vegetation, and rocks. Hurd et al. (2006) wanted to determine the proportion of residents who had a particular landscape configuration to assess the potential effect of landscape choice on urban landscape water use. To

attain those yearly water use estimates, Hurd et al. (2006) assumed that warm season turf required 25 inches of water per year (Smeal, 2013) and simply scaled the estimated water use value to reflect the proportion of turf in the landscapable area. While such broad estimates of a yearly landscape water use are customary, Al-Kofahi et al. (2012a) showed that they overestimated landscape water budgets.

Reference evapotranspiration (ET_O), which estimates water loss from an actively growing field of uniform surface of cool season grass that is ≈ 12 cm tall and not short of water (Allen et al., 2005) and a crop coefficient (K_c) are used to calculate plant water budgets. Each crop has a specific coefficient that is used with the ET_O to estimate the evapotranspiration rate for that crop (Allen et al., 2005). The crop coefficient is unitless and is computed by dividing crop evapotranspiration by ET_O (Allen et al., 1998). Crop coefficients range from 0.1 to 1.2 depending on crop type, stage of growth, and cultural practices [California Irrigation Management Information System (CIMIS), 2008]. A traditional way of applying the crop coefficient method to calculate water budgets for landscape plants is to use a landscape coefficient (K_L) instead of K_c . This change is necessary because K_c is used for a uniform species in a uniform condition, while the K_L may be used for one or more species that vary in vegetation density and microclimate conditions (Costello et al., 2000). The K_L is a product of the coefficients for species (K_s), vegetation density (K_d), and microclimate (K_m). Since K_d and K_m often are assumed to be 1 in landscape settings, K_s becomes a proxy for the K_L . Because of those approximations, the simple use of K_s to calculate water budgets is likely to produce inaccurate values.

Accurate landscape water budgets facilitate urban water conservation (Kenney et al., 2004) and the precision with which landscape

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.0929	ft ²	m ²	10.7639
3.7854	gal	L	0.2642
40.7458	gal/ft ²	L·m ⁻²	0.0245
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394

elements within the landscape are classified determines the accuracy of the landscape water budget (Al-Kofahi et al., 2012b). Because the accuracy of the landscape water budget depends in part on knowing the composition of the elements in the landscape through actual field surveys, we used a novel approach to quantitatively classify urban residential landscapes in Las Cruces, NM (Al-Ajlouni et al., 2013). We established that residential landscapes in Las Cruces could be classified into distinct landscape types based on the coverage percentage of landscape elements (Table 1). Given that we previously quantitatively classified urban landscapes, we hypothesized that a quantitatively determined residential landscape type could be associated with a specific landscape water budget. Except for our initial report (St. Hilaire and Al-Ajlouni, 2009), no report that we are aware of links quantitatively classified desert landscape types with specific water budgets. The objective of this research was to determine the relationship between landscape water budgets and quantitatively determined residential landscape types in Las Cruces, NM.

Materials and methods

LANDSCAPE CLASSIFICATION. In a previous study, we developed a method to quantitatively classify residential urban landscapes in the desert environment of Las Cruces, NM, using directly measured landscape

data. Classification methods are detailed in Al-Ajlouni et al. (2013). Briefly, the landscapable area around 54 residential homes was divided into 158 zones. All materials (elements) in the landscape were identified, measured, and categorized. Using 30% as the minimum percentage coverage area of a landscape zone that is required for a landscape element to be named as a landscape type, we classified 93% of all landscape zones into nine landscape types, namely hard-surface shade-structure, mulch, hard-surface, hard-surface-mulch, mulch tree, turf mulch, turf, tree mulch turf, and turf tree landscape types (Al-Ajlouni et al., 2013). Furthermore, the classification method developed in the previous study facilitated the calculation of a landscape water budget for each landscape type while allowing us to determine the percentage of the landscape covered by irrigated elements (plants and water features that required water to function) and nonirrigated elements (those that did not require water to function) within each landscape type (Al-Ajlouni et al., 2013).

WATER BUDGET CALCULATION. Landscape water budget for each landscape type was calculated using Eq. [1].

$$\begin{aligned} \text{Landscape water budget} \\ = \text{Plant water budget} \\ + \text{water feature evaporation} \quad [1] \end{aligned}$$

The water budget of each landscape was divided by its landscapable area to

get the water budget per unit area. This standardized the water budget for each landscape type to a per unit area basis. The plant water budget, which is the water budget for plant materials in the landscape, was calculated using Eq. [2].

Plant water budget

$$= \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \left(\frac{(ET_O)(K_{si})(0.623)(VA_{j(i)})}{IE_{j(i)}} \right) \quad [2]$$

where ET_O is annual reference evapotranspiration, K_{si} is the plant species coefficient for species i , $VA_{j(i)}$ is the vegetation (plant) canopy area in square feet for the j th patch of species i , 0.623 is a conversion unit (gallons per inch per square foot), used to express the water budget in gallons, and $IE_{j(i)}$ is the irrigation efficiency for the j th patch containing species i , which ranges from 0 to 1.

Irrigation efficiency (IE) was based on that of the Irrigation Association (2004) and was calculated using Eq. [3].

$$IE = (DU)(IME) \quad [3]$$

where DU is the lower quarter distribution uniformity and the IME is the irrigation management efficiency. Under best-case scenarios, a DU for spray and rotary sprinklers of 0.77, emission uniformity (equivalent to DU) for drip irrigation system of 0.80, and an IME of 0.90 are generally accepted (Irrigation Association,

Table 1. Landscape types in Las Cruces, NM, along with their water budget, landscape coefficient, and the coverage of irrigated elements percentage. The frequency (n = 158) of occurrence of each landscape is given.

Group	Landscape type ^z	Frequency (%)	Water budget (L·m ⁻² per yr) ^y	Landscape coefficient	Coverage of irrigated elements (%)
No-water	Hard-surface shade structure	8	0	0	0
Low	Mulch	39	162 a ^x	0.36 ab	18 a
	Hard-surface	5	61 a (166) ^w	0.16 a (0.26)	8 a (14)
	Hard-surface mulch	3	83 a (216)	0.44 bc	9 a (24)
Moderate	Mulch tree	12	656 b (734)	0.43 bc	76 b (83)
	Turf mulch	6	740 b	0.51 d	71 b
High	Turf	6	1187 c	0.55 d	102 bc ^v
	Tree mulch turf	5	1207 c	0.46 bcd	122 cd ^v
	Turf tree	9	1497 c	0.51 d	143 d ^v

^zLandscape type is based on data from Al-Ajlouni et al. (2013).

^y1 L·m⁻² = 0.0245 gal/ft².

^xNumbers that share the same letters within the column are not significant different based on Least square means separation of Tukey–Kramer test ($P \leq 0.05$). Least square means separation was done after removing outliers. Water budget groups were based on mean separation.

^wNumber in parentheses is the value before removing the outliers (unusually large water feature).

^vThe coverage of irrigated element percentages over 100% are a result of layering.

2004). Consequently, we set the IE for spray and rotary at 0.69 (0.77×0.90) and that of drip irrigation system was set at 0.72 (0.80×0.90). While other studies might prefer using other measures of DU over the lower quarter DU as we did, alternate DU and IME may be used to scale our water budget values. In this study, we noted that sprinkler irrigation systems were used mainly on turfgrass and drip irrigation was used for trees, shrubs, perennials, and annuals. We considered those two irrigation systems in our theoretical calculations.

Average annual K_s values for trees, shrubs, vines, and herbaceous plants were derived from their respective monthly K_s values. The K_s values provide a relative ranking of the water-requiring levels of landscape plants (Costello and Jones, 2000). Many K_s values are estimates that have not been verified empirically. For each plant, K_s values were mined from published sources (Al-Kofahi et al., 2012a; Costello and Jones, 2000; Desert Tropics, 2010; San Marcos Growers, 2010; Smeal et al., 2007; Sunset, 2010; U.S. Department of Agriculture, 2010) and averaged to give a single K_s value. Subsequently, K_s values were designated as very low (≤ 0.1), low (>0.1 and ≤ 0.3), moderate (>0.3 and ≤ 0.5), and high (>0.5).

However, averaging monthly grass K_s underestimated (especially that of warm season grass) the annual grass K_s due to variation between summer and winter seasons. According to the Irrigation Association (2004), monthly K_s for warm season turf was 0.18, 0.17, 0.27, 0.61, 0.59, 0.7, 0.71, 0.66, 0.66, 0.31, 0.31, and 0.21 from January to December, respectively. Monthly K_s for cool season turf were 0.76, 0.76, 0.76, 0.76, 0.76, 0.9, 0.88, 0.88, 0.76, 0.76, 0.76, and 0.76 from January to December, respectively. Those K_s values were used in water budget calculations. Therefore, Eq. [4] was used to correct the underestimation of the annual grass K_s .

$$\text{Annual grass coefficient } (K_{s \text{ grass}}) = \frac{\sum \text{Monthly grass water requirements}}{(\text{Annual } ET_O)(0.623)} \quad [4]$$

where the $K_{s \text{ grass}}$ is the annual grass water requirement per unit area, $\sum \text{Monthly grass water requirements}$ is the summation of monthly grass

water requirements, annual ET_O is the annual ET_O per unit area, and 0.623 is a conversion factor that allows the grass water requirement to be expressed on a per unit area basis. This resulted in the unit-less annual coefficients of 0.53 for warm season grass and 0.83 for cool season grass.

We used a modified Thiessen polygon method (Klein, 1989) to calculate the areas of overlapping plants. With that method, half the on-center distance between plants was used to calculate the areas of individual plants that overlapped but were in the same plane. This prevented plants' areas from being overestimated because of overlapping canopies. Where two plant canopies overlapped, but one plant's canopy was in a different plane (one plant above another) from the other, the water budget of the shaded (lower) vegetative layer was reduced by 50% or 25% when the area had partial or full shade, respectively (Houerou, 1980).

Water feature evaporation was calculated based on Eq. [5].

$$\begin{aligned} \text{Water feature evaporation} \\ = (\text{Pan evaporation})(\text{WS})(0.96) \end{aligned} \quad [5]$$

where WS is the water surface area (square feet) and 0.96 is a correction factor between annual pan evaporation (class A) and landscape water surfaces (Irmak and Haman, 2003; Smith et al., 1994). For Las Cruces, ET_O was more readily available than pan evaporation data. Pan evaporation and ET_O are highly correlated (Eagleman, 1967). In Las Cruces, historical pan evaporation is 92.8 inches per year and historical annual ET_O is 57.84 inches [New Mexico Climate Center (NMCC), 2009] making pan evaporation equal to 1.6 times the ET_O . Therefore, water evaporation for Las Cruces was calculated from Eq. [6].

$$\begin{aligned} \text{Water feature evaporation} \\ = (1.6 ET_O)(\text{WS})(0.96) \end{aligned} \quad [6]$$

where 1.6 ET_O was used instead of pan evaporation (class A).

The ET_O was the historical ET_O data calculated from a modified Penman–Monteith equation (Sammis et al., 1985). The ET_O was retrieved from the Fabian Garcia Science Center weather station, Las Cruces, NM

(NMCC, 2009). Water features encountered during data collection were swimming pools, fountains, and ponds.

LANDSCAPE COEFFICIENT. For each zone, the landscape coefficient (K_L), which is the sum of the weighted mean of each irrigated element coefficient based on its coverage area, was determined from Eq. [7].

$$K_L = \frac{\sum_{i=1}^{\infty} (K_{si})(PA_i) + \sum_{n=1}^{\infty} (K_{s \text{ grass } n})(PA_n) + \sum_{l=1}^{\infty} (K_{wl})(WS_l)}{\sum_{i=1}^{\infty} (PA_i) + \sum_{n=1}^{\infty} (PA_n) + \sum_{l=1}^{\infty} (WS_l)} \quad [7]$$

where the K_{si} is the annual species coefficient for plant species i , PA_i is the plant canopy area for the plant species i , $K_{s \text{ grass } n}$ is the annual grass coefficient for grass type n , PA_n is the area of grass n , K_{wl} is the annual water coefficient for water surface l , and WS_l is the water surface area l . The K_w is a substitution for the product of pan evaporation and 0.96. Thus, K_L weights irrigated elements in the landscape regardless of the area they occupy in the landscape. The K_L values used in this manuscript are unique and are based strictly on Eq. [7].

STATISTICAL ANALYSIS. We used SAS statistical software (version 9.2; SAS Institute, Cary, NC) for all statistical analyses. Significance was defined for $P < 0.05$. A mixed model was used to compare water budgets and the coverage of irrigated element percentages among landscape types. One landscape type, hard-surface shade-structure was removed from the analysis due to uniform zeros. The hard-surface shade-structure had a zero-water budget. When differences among landscape types were detected, the Tukey–Kramer mean separation test was used.

For water budget and the coverage of irrigated element percentage, there was evidence of unequal variance with the observed variance tending to increase with increasing mean and, non-normality due to positive skew. Therefore, we used the power-of-the-mean model to analyze those variables. We used a modified outlier strategy (Ramsey and Schafer, 2002) to assess sensitivity of the analysis to skew. Observations with studentized residuals that were greater than three were removed before conducting mean separation. Three outliers were removed from each water budget and

the coverage of irrigated element percentage.

The K_L values for the landscape types were fitted to two variances using the Proc MIXED model. Landscape types with similar water budgets were sorted into the same group. The SAS Proc CORR model was used to assess the correlation between water budget and each of K_L and irrigated element percentage. SAS Proc GLM model was used to determine if there were significant differences between regression lines of water budget and both K_L and the percent coverage of irrigated elements.

Results and discussion

We classified 93% of the landscape zones into nine landscape types (Al-Ajlouni et al., 2013). Interestingly, these nine landscape types clustered into only four water budget categories (Table 1). If the hard-surface shade-structure landscape type, which had neither plants nor water features, and consequently had a water budget equal to 0, is discounted, then only three water budget groups emerge. This result implies that landscape water use managers in the desert environment of Las Cruces might be able craft water management strategies for just a few water budget categories instead of several landscape types.

With landscape water budgets ranging from 61 to 162 $L \cdot m^{-2}$ per year, the mulch, hard-surface, hard-surface-mulch landscape types clustered into a group that can be considered a low-water budget group. The low-water budget group formed 47% of the landscape types. This number is remarkably consistent with that of Hurd et al. (2006), which showed that “native/natural desert landscape” and “rocks, gravel, and bare soil,” all included in our low-water budget group, formed 46% of landscape types in Las Cruces. The relatively high percentage of landscapes in the low-water budget group further reiterates Las Cruces homeowners’ awareness of the importance of the water issues that face the state and their community (Hurd et al., 2006).

That the moderate-water and high-water budget groups formed 38% (Table 1) of the landscape types suggest that opportunity exists to adopt urban landscapes that have a reduced water budget. Converting

landscapes in high- and medium-water budget landscapes to low-water budget landscapes will reduce the overall water budget allocated to urban landscapes. And there are good reasons why this is true. In the desert city of Las Vegas, NV, converting from traditional landscapes (a high-water budget group) to xeriscape landscapes (a low-water budget group) saved up to 76% of irrigation water (Sovocool et al., 2006). In Florida, urban landscapes that had an average irrigated area of 35% turfgrass (a high-water use element) and 65% landscape bedding plants consumed 39% less irrigation than those configured with 75% turfgrass and 25% landscape bedding plants (Haley et al., 2005).

One unexpected result was that as an aggregate coefficient, K_L had a weak relationship ($r^2 = 0.3$) with water budget (Fig. 1). The heterogeneity of coefficients that contribute to the K_L might partially explain why this is so. For example, the mulch landscape type, a low-water budget group, had a K_L of 0.36 and a water budget of 162 $L \cdot m^{-2}$ per year. At the other end of the water budget spectrum was the tree mulch turf landscape type, a high-water budget landscape group with a water budget of 1207 $L \cdot m^{-2}$ per year (Table 1). Even with a landscape water budget that was 1045 $L \cdot m^{-2}$ per year more than that of the mulch landscape type, the K_L of 0.46 for the tree mulch turf landscape type was statistically similar to that of the mulch landscape type. We attribute the

similarity to the large statistical variance of the K_L (Table 1).

Our data clearly show that the percent of landscape area with plant canopy and other irrigated elements covering it correlated more strongly ($r^2 = 0.95$) with water budget than K_L (Fig. 2). These results suggest that the percent of the coverage by irrigated elements is more relevant to water conservation than the K_L of the material. Our results are also in line with the empirical data of Sun et al. (2012) who showed that canopy cover, not type or water use level, dictates plant water use. While many public awareness programs and nurseries encourage the use of low-water use species (low K_s) in managed landscapes as a water conservation method, our data show that percentage of plant cover regardless of the species should not only be considered, but may be the strongest indicator of landscape water use.

Furthermore, these results might have implications for how homeowners select and manage plants in desert environments. Homeowners typically select plant taxa mainly based on their aesthetic value (Spinti et al., 2004; St. Hilaire et al., 2008; Yabiku et al., 2008), functionality, availability, and cost (Spinti et al., 2004) and not on their water use level. In contrast, plant-based water conservation campaigns for desert environments often focus on curtailing the use of high-water use plants. Our data suggest that limiting the percent plant cover rather than the type of plant might be

Fig. 1. Correlation between water budget and landscape coefficient (K_L) for urban landscapes in Las Cruces, NM; $1 L \cdot m^{-2} = 0.0245 \text{ gal/ft}^2$.

Fig. 2. Correlation between water budget and percentage of the coverage of irrigated elements for urban landscapes in Las Cruces, NM; $1 \text{ L} \cdot \text{m}^{-2} = 0.0245 \text{ gal/ft}^2$.

a more effective strategy for water conservation. This might be a strategy that is worthy of pursuit for homeowners wishing to have expanses of plants in the urban landscapes, or small oases of mesic or hydric plants while doing their part in urban landscape water conservation. In addition, given that desert-adapted plants require minimal supplemental watering once established (Yabiku et al., 2008), further research is needed to determine if the impact of plant cover on water use varies as plants mature.

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